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Selected technical problems of cogeneration of electric energy and heat

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Abstract

The paper is focused on selected technical problems of cogeneration of heat and electric power (combined heat and power – CHP) both in a large and small scale. First, large-scale cogeneration systems applied in large power industry are discussed and results of adaptive control of extraction condensing turbines are presented. Then, advantages of distributed cogeneration are pointed out and small-scale cogeneration systems aimed for modernisation of a fossil-fuel district heating plant are investigated. At the end of the paper, organic Rankine cycle (ORC) heat and power units are described for biomass-fuelled cogeneration and topping of main generation units to use the recovery heat.

Keywords: Cogeneration of electric energy and heat; Extraction-condensing turbine; Adaptive control; Distributed cogeneration; Organic Rankine cycle; Recovery heat

1 Introduction

Cogeneration as a simultaneous production of electric energy and heat brings a considerable increase of energy efficiency and contributes to decrease emissions of harmful gases into the environment. Cogeneration can be applied in a large and small scale, however the opportunities for cogeneration are usually determined by the demand on heat. The prime movers in the large-scale cogeneration are steam turbines operating in a closed

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Rankine cycle, including back-pressure and extraction-condensing turbines [1]. In the back-pressure turbine, steam gives away its remaining superheat and condensation heat for heating of district net water. One asset of the back-pressure turbine system is its simplicity, another is a low demand for cooling water and low heat losses in the condenser. Among a number of disadvantages are a short expansion line (with the region of low pressures and temperatures exempted from the electric energy production) and a large stiffness of the system, that is the dependence of the electric energy production on the demand on heat.

In the extraction-condensing turbine, an extraction point is located one, two or more turbine stages upstream of the outlet diffuser. Expansion of steam in the extraction-condensing turbine can take place down to the parameters below 0.1 bar and 40 °C, which is important for the purpose of production of electric energy. A disadvantage is a heat loss in the condenser, however extraction-condensing turbines provide the possibility of flexible coping with heat demand with practically little loss to the electric energy production. In order to take full advantage of variable load operation in extraction-condensing turbines, their adaptive control is needed and will be discussed in Section 2 of this paper.

Cogeneration can especially be applied in small power units of distributed cogeneration systems [2,3]. The development of these small power units is not centrally planned. Probably the most adequate division of distributed cogeneration units according to the generated power is as follows:

- micro units (up to 5 kWe),
- small units (5 kWe – 5 MWe),
- medium units (5 MWe – 50 MWe).

In small (and micro) units, the produced energy goes first to local communities. One can mention here the energy generation for households, residence buildings, large farms, public buildings or small and medium enterprises. The surplus of electric energy goes to the power network, whereas heat surplus goes to local district heating networks. Among several advantages of distributed cogeneration are:

- utilisation of local energy resources, especially renewable energy,
- reduction of green-house gas emissions (cogeneration on renewable energy sources),
- increasing energy safety by diversification of fuels,
- reduction of transmission losses,

- avoiding excessive installed power in a single location.

There are many different technologies available for cogeneration of electric energy and heat in distributed sources such as gas/biogas stations, pv/solar instalations, biorafinery, biomass stations. The paper describes an idea of a multi-fuel cogeneration system, which is a local energy centre for a small municipal community that includes a biomass-fueled steam power unit, ORC power unit, a group of gas piston engines and a coal boiler.

A promising technology for cogeneration based on local energy resources is organic Rankine cycle (ORC) technology [4,5]. In this Rankine-like technology the power unit is driven by a vapour of a working medium other than water. There is a variety of available working media which can be effectively selected for a wide range of operating conditions. An ORC power unit can be used as a main generation system allowing utilisation of different types of fuels. The solution also offers a possibility to apply low temperature heat sources. Therefore, ORC can be applied for topping main generation systems, for example based on piston engines or gas turbines. In the first case, a biomass-fueled boiler can be a heat source, whereas in the latter case ORC operates on a recovery heat coming from the exhaust gases and/or engine cooling system. The ORC unit working in a combined cycle allows for a considerable increase of electric energy production. Both applications are developed at IMP PAN in the framework of the strategic programme of the Polish National Centre for Research and Development (NCBiR) and are described in the paper.

2 Adaptive control for extracting-condensing turbines for large-scale cogeneration

One way to adapt blading systems of extraction-condensing turbines to variable load operation during cogeneration of electric energy and heat is adaptive control. The main element of adaptive control is the so-called adaptive stage of flexible geometry located directly downstream of the extraction point. During extraction of steam to the extraction point this flexible geometry enables reduction of the mass flow rate in the blading system without a reduction of pressure drop in downstream stages. Thus, the full available pressure drop is used in the blading system. Expansions beyond the blading system, involving a loss of turbine power and giving rise to uncertainty in operation of the exit diffuser, are avoided.

In the most typical designs of large turbines, for example manufactured by LMZ, ABB-Zamech, Alstom Power [6,7] the adaptive stage has throttling nozzles that have movable leading edges blocking part of the blade-to-blade passage if necessary (Fig. 1 – part A). Another design of the adaptive stage nozzles has the same driving mechanism and a more complex division line of the stator blade (Fig. 1 – part B). A design of adaptive stator blades for both large and small turbines with a rotated trailing edge (flap nozzle) which controls the throat was patented in [8] (Fig. 1 – part C). As compared to the design with movable leading edges, this design maintains the smoothness of the profile shape, also for low levels of throat opening. A similar principle lies behind the system with rotated stator blades (Fig. 1 – part D).

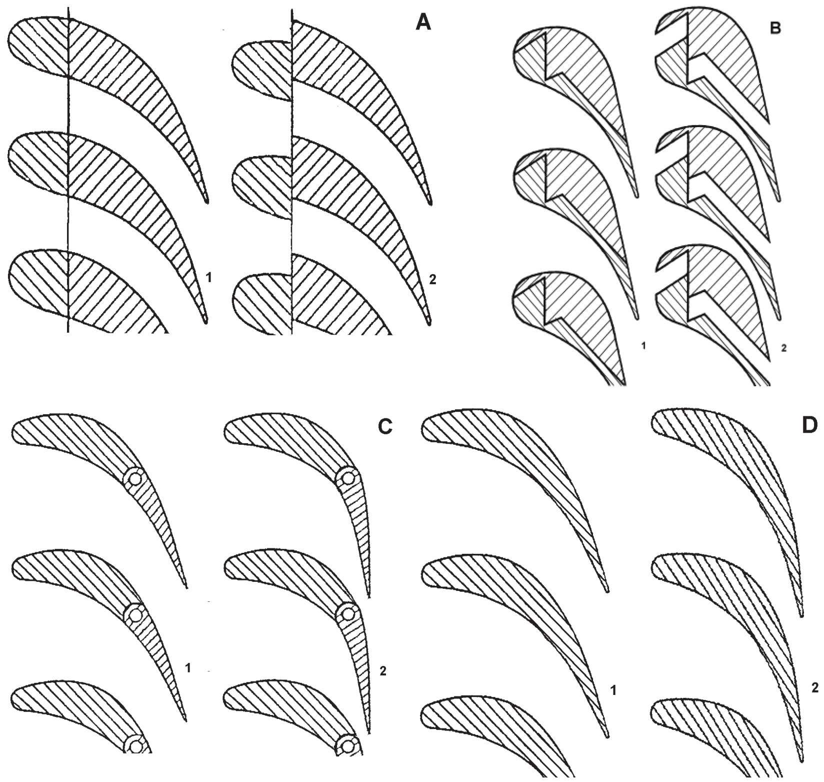

Figure 1: Adaptive stage nozzles: blade with a movable leading edge (A), blade with a complex division line (B), blade with a rotated trailing edge – flap (C), rotated blade (D); 1 – full opening, 2 – part-load opening.

The numerical analysis of effects of adaptive control in a group of stages of a large power LP turbine of 50 MWe (as in Fig. 2) based on the rotated blade design is presented in [9,10]. The calculations were made using a CFD code FlowER [11] in a single blade-to-blade passage of a group of two exit stages (last and last-but one stage). The computational method makes use of the RANS model, still the most effective for turbomachinery flow simulation [12].

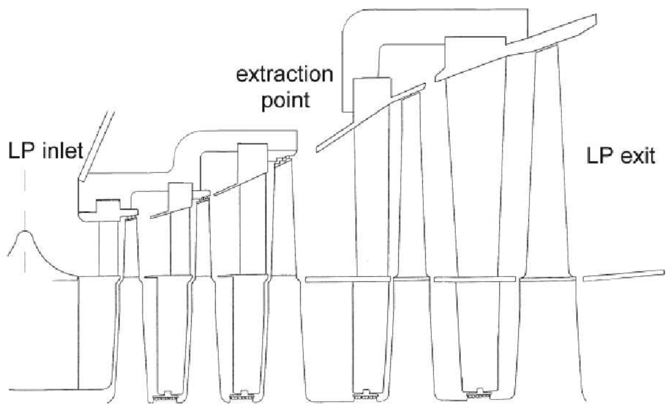

Figure 2: Geometry of the flow system of an LP extraction-condensing turbine in meridional view.

Figure 3 exhibits changes of power in the stage group as a function of mass flow rate during extraction of steam to the extraction point. Changes of power are plotted for different stator blade stagger angles (coloured solid lines) and for different pressure drops through the stage group (coloured dashed lines). Several point are marked to help to estimate the advantages of adaptive control. They are: N – nomianal operation point; A – sample operation point under conditions of extraction of additional 10% of the turbine mass flow rate to the extraction point, and A′ – the same point of operation after adaptive control. The aim of adaptive control is to take advantage of the full pressure drop available and to bring the expansion back to the turbine blading system. As it follows from Fig. 4, this can be achieved by closing last-but-one stator throats and rotating the blades by 2°. Point A is then moved to point A′ that lies on the line of nominal pressure drop in the stage group from 0.39 to 0.10 bar. A significant reduction of flow losses especially in the last stage can be achieved as a result of that. For a considered extraction-condensing 50 MWe turbine, power gains reach on average 2.5 MWe per downstream stage under conditions of a 10% mass flow rate extraction to the extraction point located upstream of a group of two exit stages. The stage group power is then lower by about 11% than the power before the steam extraction (6.5 MW), and is practically decreased by the decreased mass flow rate through the blading system. Note that the power increase obtained from the adaptive control amounts to about 10% of the turbine power.

3 Multi-fuel cogeneration system for a local energy centre

There is a vast potential in Poland, also in other countries, for modernisation of outdated coal-fired heat stations and their upgrade to heat and power stations that assure a high-efficient cogeneration. This transformation can apply to objects ranging from a few up to even a few hundreds MWt of heating power. The strategy for modernization of local heat stations was worked out under the strategic programme of National Centre for Research and Development entitled: Advanced technologies for the production of energy, Task 4. Elaboration of integrated technologies for the production of fuels and energy from biomass, agricultural waste and other wastes [13]. In this paper an idea how to modernise a local heat station of heating power below 25 MWt is described. The idea consists in topping of the existing infrastructure with the cogeneration units as well as in diversification of fuels with a change to ecological fuels. In order to increase the share of renewable energy in the energy balance of the modernised station, some new installations will be supplied by biomass, other by natural gas. Part of the existing coal boilers will be modernised to increase their efficiency and reduce emissions to the atmosphere.

The analysis of operation of heat stations shows a considerable differences in heat demand between the high and low season. The heat demand in the high season is by 1 to 2 orders of magnitude higher that in the low season, which can be observed in Fig. 4. The new infrastructure should be modular allowing for sequential switching on subsequent heat and power units according to the changing heat demand. On the other hand, new units of the system should operate as long as possible to maximise incomes from the energy production. The elaborated idea of a combined heat and power (CHP) system consists of four elements, Fig. 5:

1. A biomass-fueled ORC CHP unit including an oil boiler of power

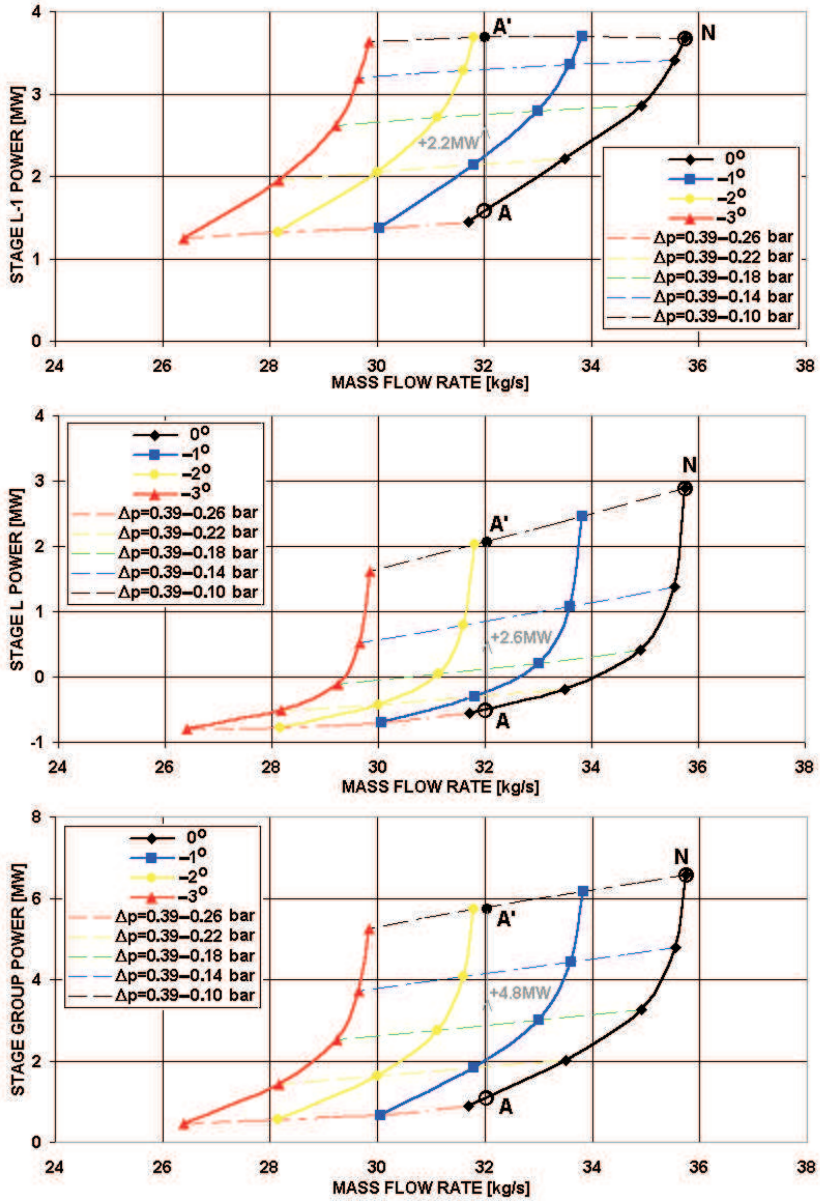

Figure 3: Changes of turbine stage group power as a function of mass flow rate.

1.8 MW fed by wood chips or pellets, intermediate loop of thermal oil, ORC loop with a generator of electric power 0.24 MWe, heating

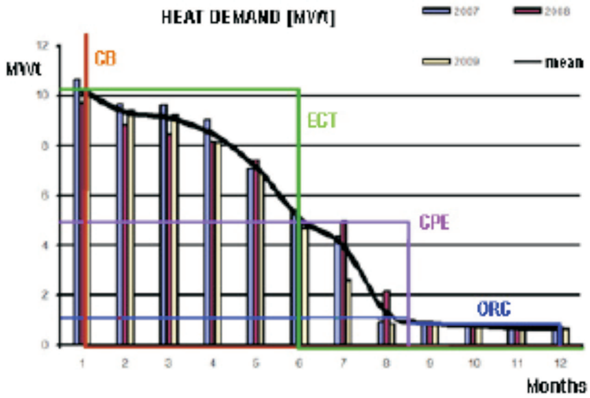

Figure 4: Yerly heat demand and heat generation from four modules.

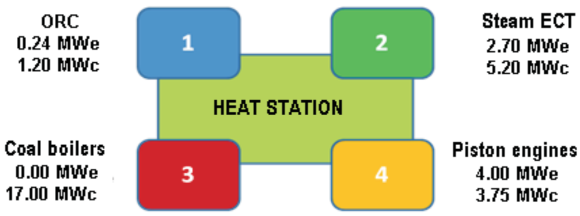

Figure 5: Scheme of modernisation of a 25 MWt heat station.

system of power 1.20 MWt and a heat accumulator of capacity 200 m^3. The heat power of the ORC unit is tailored to the heat demand during the low season, however the unit will operate both during the low and high season.

2. A natural gas piston engine cogeneration system including two combustion piston engines (CPE) with generators of total electric power 4 MWe and heating system of power 3.75 MWt. Due to a high price of natural gas this system is designed only for seasonal heating and high-efficiency cogeneration.

3. A biomass-fueled steam CHP unit including a steam boiler of power 11 MW fed by wood chips or pellets, steam unit with an extraction-condensing turbine (ECT) and generator of electric power 2.7 MWe and a heating system of power 5.2 MWt. The steam unit is designed for all-year operation. Within the high heating season it will operate

in a heating (extraction) mode, whereas in the low season it will work in the condensing mode with a maximum production of electric energy.

4. A group of modernised coal boilers (CB) of heating power 17 MWt; These coal boilers will operate only to cover the peak demand for heat.

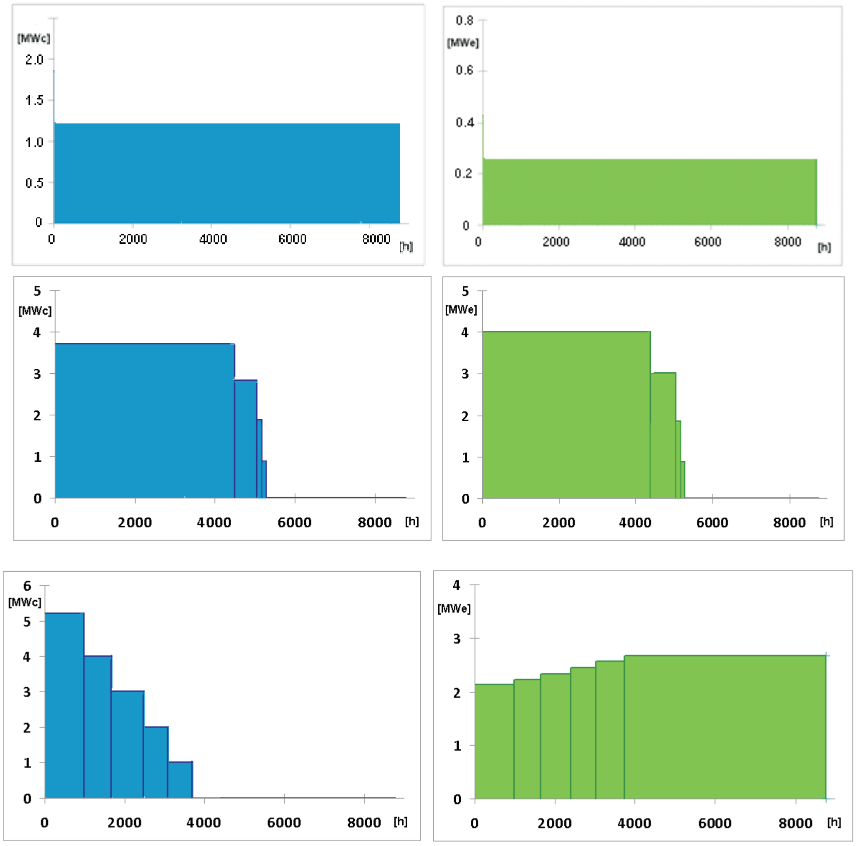

Figure 6: Yearly distribution of generated heating (left) and electric (right) power from the ORC unit (top), piston engines (centre) and steam unit (bottom).

This four element structure of the modernized heat and power station is consistent with the yearly heat demand, Fig. 6. For the heating power up to 1.2 MWt, the ORC unit operates in cogeneration. Also the steam unit (ECT) works in the condensing mode. For the heating power of

1.2–5.0 MWt piston engines are also switched on, the steam unit (ECT) working still in the condensing mode. For the heating power of 5.0–10.2 MWt all the above units are working, the steam unit (ECT) working in the heating mode. Above the heating power of 10.2 MWt, coal boilers begin to operate. The yearly distribution of generated heating and electric power from subsequent units is presented in Fig. 6.

The described variant of modernization fulfils the yearly heat demand of 40 GWht and yields the production of electric energy of 39 GWhe. The ORC and CPE units work all time in high-efficient cogeneration, whereas the steam ECT unit fulfils the high-efficiency cogeneration condition only during its operation with the maximum heating power. The yearly mean heating power from all units is equal to 4.66 MWt, electric power – 4.5 MWe. Table 1 gathers values of mean yearly power supplied in fuel, N_F, electric and heating power, N_e and N_h, yearly amount of energy supplied in fuel, Q_F, produced electric energy and heat Q_e and Q_h for 90% availability of the units, electric efficiency and cogeneration efficiency η_e and η_{cog}, yearly demand for fuel as well as primary energy saving coefficient (PES) for the presented variant of modernization.

Table 1. Technical output of the modernised local energy centre.

UNIT	?t (hour)	N_h [MW]	N_e [MW]	N_F [MW]	Q_F [MWh]	Q_e [MWh]	Q_h [MWh]	η_e	η_{cog}	Fuel: CB-coal [Mg] ORC,ECT-wood [Mg] CPE-gas [$10^6 m^3$]	PES [%]
CB	8760	0.569	0.000	0.948	8 301.67	0.00	4 981.00	0.000	0.600	1 358	-
ORC	8 760*0.9	0.954	0.188	1.436	12 575.93	1 646.31	8 357.67	0.131	0.795	3 353.58	14.49
CPE	8 760*0.9	1.906	2.033	4.580	40 121.85	17 805.29	16 699.50	0.444	0.860	4.127	23.53
ECT	8 760*0.9	1.229	2.278	10.101	88 488.78	19 954.16	10 765.98	0.225	0.347	23 597.01	-21.24 (10.33)*
	Yearly mean power CB+ORC+CPE+ECT	4.658	4.498	SUM of energy CB+ORC+CPE+ECT		39 405.76	40 804.15	*only during operation with the maximum heat power of 5.2 MWt			

4 Organic Rankine cycle technology

The equivalents of large power turbines for distributed cogeneration systems are small steam turbines or small turbines that operate in an organic Rankine cycle (ORC) with a working medium other than water vapour. There are a number of working media available for ORC, which should be selected based on their thermodynamic properties so as to assure the highest possible efficiency of the cycle for the available range of cycle temperatures. The working media should also be characterised by low global warming potential (GWP) values, should remain non-toxic, non-corrosive and chemically stable. The main applications of ORC are cogeneration systems of power up to 1 MWe and low-temperature heat recovery systems [14,15].

A model of CHP ORC unit of 100 kWe built at IMP PAN in Gdańsk is shortly described. Its main components are: ecological boiler, intermediate heat cycle to extract heat from flue gases and pass it to thermal oil, which has a role of a heat carrier, main heat cycle including the evaporator, turbine driving a generator, recuperator, condenser and circulating pumps for the working medium and thermal oil. The working medium in the ORC cycle is silica oil MDM. The intermediate liquid is hightemperature oil Therminol66. The condensation heat of the working medium is used for heating net water. A scheme of the CHP unit is presented in Fig. 7. Its main parameters are:

- thermal oil loop
  - 310 °C/200 °C
- ORC (MDM) loop
  - turbine-vapour pressure 12/0.17 bar,
    vapour temperature 280 °C/230 °C
  - recuperator-vapour 230 °C/138 °C, liquid 90 °C/176 °C,
  - evaporator – 280 °C,
  - condenser – 90 °C,
  - hot water (winter) – 80 °C/60 °C.

Two versions of a turbogenerator are designed:

- a classical version of a turbogenerator with an axial multi-stage turbine of rotational velocity 9000 rev/min [16],
- a hermetic version with the turbine and generator operating in one compartment with a radial single-stage turbine of rotational velocity 20000 rev/min [17].

The analysis of energy efficiency of the presented cycle shows the cogeneration efficiency of 87%, whereas the efficiency of production of electric energy reaches 17%. The solution offers a possibility of utilisation of different types

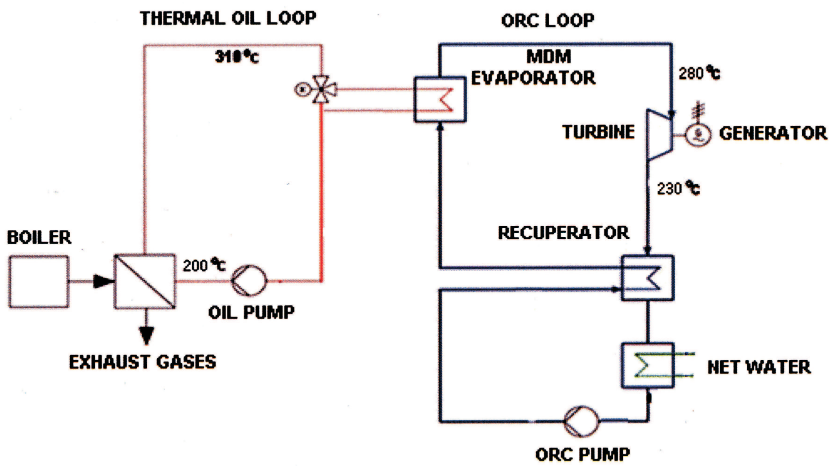

Figure 7: Scheme of a 100 kW CHP ORC unit.

of fuels, the preferable is low-grade fuel, eg. wood chips. It is a model for CHP units dedicated for communal energy centres with a total heat capacity of 0.5–5 MWt and electric power 0.1–1 MWe. Micro CHP units dedicated for individual households of total heat capacity up to 20 kWt and electric power up to 4 kWe are also developed [18,19].

Another example of application of ORC technology is a heat recovery unit. The main generation unit is here a combustion piston engine fed by natural gas (in practical applications biogas and syngas can also be used). The ORC unit increases the efficiency of electric energy production or the whole gas/vapour ORC system. The ORC unit topping the engine cycle can operate either in cogeneration where it uses both exhaust gas and cooling heat or without cogeneration. In the latter case the ORC unit uses the heat from exhaust gases for the maximum production of electric energy, whereas the engine cooling heat can be used for net heating purposes. This variant is shown schematically in Fig. 8. In the presented cycle, the ORC working medium is SES36. The intermediate medium is thermal oil Veco5HT. The engine is equipped with the heat recovery system consisting of:

- a heat exchanger to recover the cooling heat of the engine (water to water),
- a heat recovery boiler to recover heat from engine exhaust gases (exhaust gases to thermal oil).

A simulation of composition of exhaust gases was made and a minimum temperature of exhaust gases leaving the engine was evaluated so as to avoid their condensation in the heat exchanger. The main cycle parameters are:

- thermal oil loop
  - temperature 170 °C/100 °C
- ORC (SES36) loop
  - maximum pressure 16 bar, maximum temperature 145 °C,
  - condensation pressure 1.6 bar, condensation temperature 45 °C.

Two versions of expander are prepared for this installation:

- a pneumatic engine with rotating pistons of 3000 rev/min in a hermetic casing with a generator,
- a radial-axial flow high-reaction single-stage turbine of 15000 rev/min also in a hermetic casing with a generator [16].

The calculated efficiency of the ORC cycle reaches 16%, which can raise the efficiency of electric energy production in the gas/vapour ORC cycle up to 50%. This is very important in case of a low demand for heat in cogeneration systems. The idea of maximising electric energy production by means of combined two or multi-fluid cycles is also known in large power engineering [20,21].

5 Summary

It is shown that adaptive control in a cogeneration large-power extraction-condensing turbine can give considerable efficiency gains by virtue of proper utilisation of the available pressure/enthalpy drop in the turbine. For a 10% mass flow rate extraction to the extraction point located upstream of a group of two exit stages of a 50 MWe turbine, power gains reach on average 2.5 MWe per downstream stage.

The assets of distributed small-scale cogeneration and a number of ecological cogeneration technologies suitable for diversification of fuels are also discussed. The idea of a modular multi-fuel cogeneration system for a local energy centre of a small municipal community that includes a biomass-fueled steam power unit, ORC power unit, a group of gas piston engines and coal boiler is shown to suit very well the yearly heat demand conditions.

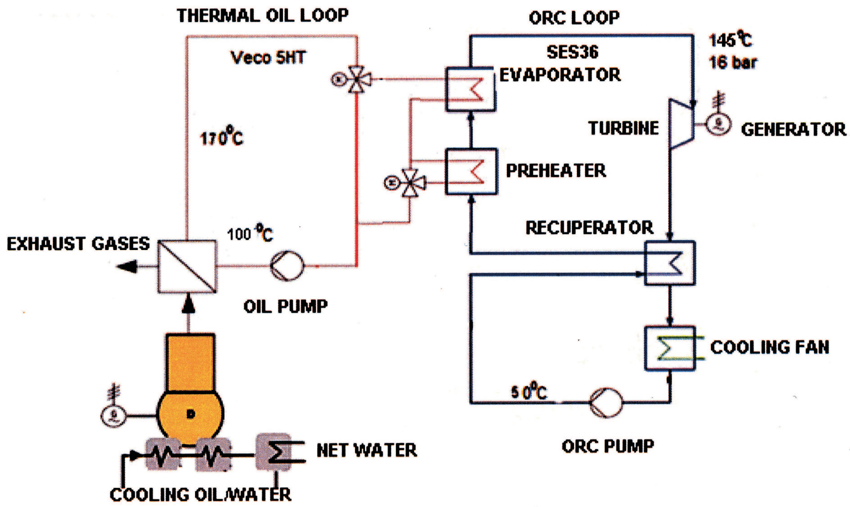

Figure 8: The ORC unit topping the combustion piston engine cycle.

The paper is also focused on ORC technology, first to be used as a small-scale main generation system allowing utilisation of low-grade fuels, and second, to be applied for topping main generation systems, for example based on piston engines or gas turbines, to utilise the heat recovered from exhaust gases and/or cooling heat.

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   etc.
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   [1] `Holman J.P.:` *`Heat Transfer.`* `McGraw-Hill, New York 1968.`

   (b) for journals: the name of the journal, volume (Arabic numerals in bold), year of publication (in round brackets), number and, if appropriate, numbers of relevant pages, for example:
   `[2] Rizzo F.I., Shippy D.I.:` *`A method of solution for certain problems of heat conduction.`* `AIAA J.` **8** `(1970), No. 11, 2004-2009.`

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